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TSS Subsatellite Attitude Dynamics and Control Laws Verification Programs

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TSS SUBSATELLITE ATTITUDE DYNAMICS AND CONTROL LAWS VERIFICATION PROGRAMS

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Abstract- This paper deals with the presentation of a dynamic model of the Tethered Satellite System and of the relevant simulation program, developed in order to provide the dynamic analysis support for the design verification of the Subsatellite attitude control. A special care has been spent in the Satellite attitude dynamic analysis and the model has been specifically conceived to this aim.

The way in which the simulation results can be utilized for the verification and testing of the attitude control is also presented.

1 - INTRODUCTION

The design of the Attitude Measurement and Control Subsystem (AMCS) of the TSS-Subsatellite for the electrody-

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namic mission has been completed and now it is going to be verified and tested. A representative dynamics of the system is one of the main items that has to be implemented for the design verification phase and in such an optic a dedicated program has been developed.

The aims of this program are:

- to investigate the dynamics of the system, with a particular interest for the Satellite attitude behaviour, and to identify potentially critical areas for the AMCS performance verification;

- to provide realistic input data for the verification and testing phases.

To this purposes a model representing the overall Orbiter-tether-Satellite system has been considered and developed, while the adoption of a simplified, provided representative, AMCS model is enough for the goal.

On the other side, to the AMCS performance verification aim, a complete and accurate model is needed for the AMCS itself, requiring a small integration step (128 msec), tied to the high on-board data handling sampling rate. The need for the implementation of a simplified dynamic model (3 satellite rotational d.o.f + the possible elastic ones) arises then, in order to avoid unaffordable CPU times.

The "dynamic-simplified" model can be called an 'open loop' approach because it assumes that the overall system dynamics impacts on the Satellite attitude, while the fact that the attitude is controlled has a negligible effect on the overall behaviour, this resulting in the tether tension at the swivel point which does not depend on the Satellite attitude. This seems to be a reasonable hypothesis, to be anyhow validated by means of the "AMCS-simplified" model, which, in turn, can be called the 'closed loop' approach, as it accounts for the coupling between the satellite attitude and the overall dynamics, while being not burdened by low integration step requirements.

The simulation results of the 'closed loop' model will then be used as input data for the "dynamic-simplified" model runs; in fact, in order to provide an adequate capability to represent the system, the "dynamic-simplified" model requires, for each run, the force time history at the tether attachment point and the firing sequence of the Satellite thrusters not driven by the AMCS (in plane and out of plane thrusters) in input.

The results of the 'closed loop' simulations will also be used for the integration and testing phase: the AMCS hardware and software will work, by means of gyros and sensors stimulators, in closed loop with a simulated real-time-computed system dynamics. The same 'open loop' model as for the verification analyses will be used to provide the necessary input to the stimulators.

At the moment, the 'closed loop' model has been implemented and the program is undergoing integration tests, while the first simulation runs will be performed in a short time.

Hereafter the 'closed loop' model and program are described.

2 - MODEL DESCRIPTION

2.1 - Configuration

The electromagnetic mission will be supported by the Shuttle in an approx 300 km orbit; the Satellite will be deployed upward up to 20 km from the Orbiter; the Satellite mass will be approx 500 kg.

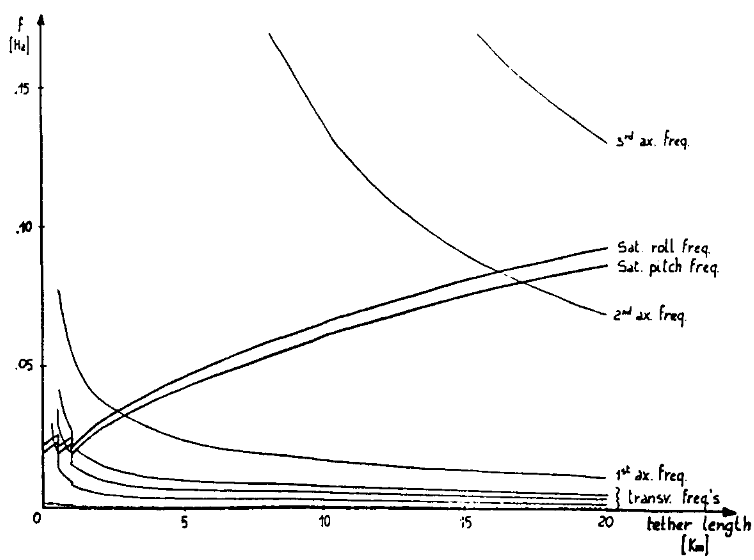
Only the Satellite yaw axis is controlled, stabilization on the other two axes being assured by the gravity gradient. During on-station phase, the Satellite spins about the yaw axis and the spin rate is controlled (1 rpm). During retrieval, the yaw angle is controlled in such a way to allow for the in plane and out of plane thrusters to fire in the correct direction for libration control. During the on station phase, two deployable booms, part of the scientific experiment, will be extended to approx 4m.

2.2 - Tether Model

Some preliminary analyses showed different kinds of behaviour of the system depending on the tether length. This leads to different representations of the system, depending on the deployed length. In figure 1 the main system frequencies are given as a function of tether length (ℓ).

The frequencies of the Satellite oscillations about its roll and pitch axes decrease as ℓ decreases; the gravity gradient stabilizing effect for these axes also decreases, support in tensioning the tether being provided at short distances by in-line thrusters.

Fig. 1



The longitudinal frequencies of the overall system due to tether elasticity decrease as ℓ increases. It can be seen that the axial frequencies may couple with the pitch/roll oscillations. The number of modes to be taken into account depends on the tether length: at short distance only the first axial mode is significant, while the others could be neglected, leading to a reduction of the integration step without affecting the system behaviour representation; at the longest tether extension also the second mode has to be considered.

The string vibration too may have a significant coupling with the Satellite oscillation at short tether length.

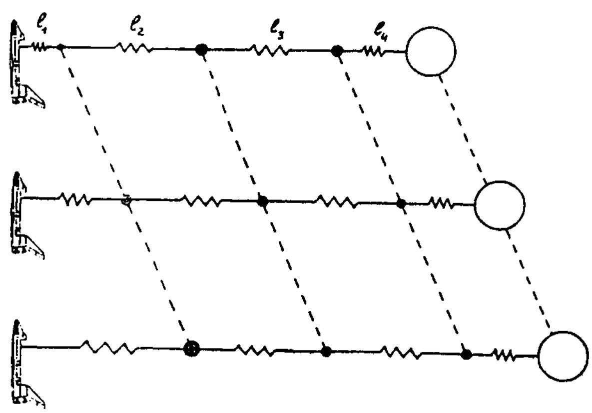
These considerations lead to the need of considering in any case the tether mass and elasticity: a lumped mass approach for describing the tether was chosen, where the number of masses is selectable as a function of tether length.

The tether can be modelled as a massless spring connecting the Orbiter and the Satellite; in such a way only the first axial mode is simulated. To include the other modes, the tether is described by mass points connected by springs whose stiffness depends on the undeformed tether length between adjacent bodies.

During deployment and retrieval the tether mass changes: this is represented by changing the mass of the mass point closer to the Orbiter; the other mass points maintain their mass. The nominal (unstressed) tether length between the Orbiter and the closer mass point also changes (and so its stiffness does), according to tether reeling, while the unstressed tether length between the other masses remains unchanged.

The number of mass point cannot be changed during the simulation in the current version of the program. The fixing of this number at the beginning of each run allows for introducing only the frequencies of interest during each part of the mission.

Fig. 2



When, during deployment, the need for considering another frequency appears, the simulation requires a restart with a new description of the tether which takes into account new mass points. The I.C. for such a new configuration can be derived from the results of the previous simulation, under the assumption that the new modes are not excited; thus, the new masses must be added until the associated mode effects are negligible. Reverse considerations can be applied for the retrieval phase.

An alternative/complementary model is being developed, to be used for cross validation purposes: the mass points are maintained uniformely spaced along the tether length to represent the actual mass distribution, during both deployment and retrieval. The system frequencies are now closer to the actual ones, but the mass points "move" along the tether.

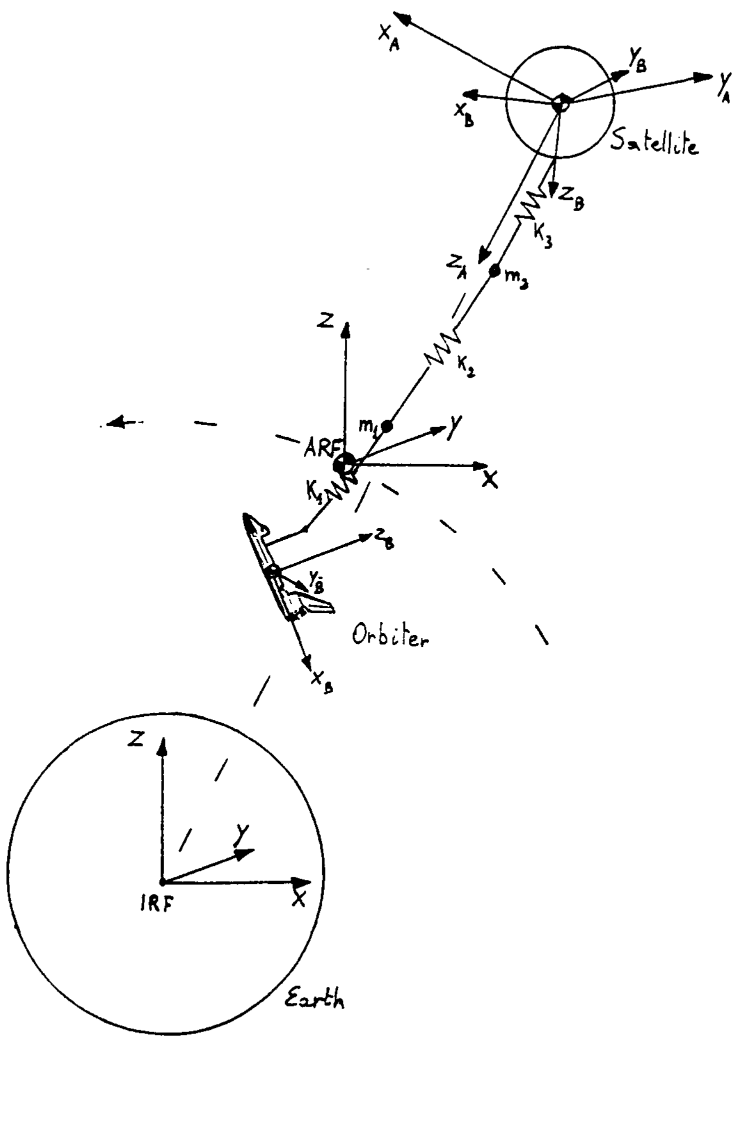
2.3 System Model

The Orbiter and the Satellite are considered rigid bodies connected by a tether represented by series of springs and point masses. The system is considered orbiting around the Earth.

The references frames, showed in figure 3, are:

- Inertial reference frame (IRF), located in the centre of the Earth.

Fig. 3



X_A
Y_B
Y_A
X_B
Satellite
Z_B
K_3
Z_A
m_3
Z
K_2
m_1
Y
ARF
X
K_1
z_B
y_B
Orbiter
x_B
Z
Y
IRF
X
Earth

- Accelerating reference frame (ARF), in the centre of mass of the overall system; it is always parallel to the IRF. The motion of ARF origin is described with respect to IRF, integrating the orbit equations of the system. The motion of the parts of the system is described with respect to ARF. This is to avoid possible numerical problems when the motion of a system is referred to a very far reference frame (small numbers added to large numbers).

- Orbiter body reference frame, located in the Orbiter c.m.

- Satellite body reference frame, in the Satellite c.m.; z-axis is directed toward the tether attachment point.

- Satellite attitude reference frame, in the Satellite c.m., with the z-axis always directed toward the Earth centre. The Satellite attitude is referred to this frame (local vertical).

2.4 Dynamic Equations

The motion of each body is computed with respect to ARF. The Orbiter has 3 translational rigid d.o.f's; the 3 rotational d.o.f.'s can be taken into account or neglected, according to the figure of an input flag. The Satellite has all the 6 rigid d.o.f.'s. The mass points describing the tether have only 3 translational d.o.f's.

Three differential equations describe the orbital motion of the origin of ARF about the Earth.

The translational differential equations with respect to ARF are obtained for each body considering all the forces acting on it (actual and apparent ones):

$$m\ddot{\bar{x}} = -m\bar{A} + m\bar{g} + \bar{T} + \bar{F}$$

where: $\bar{x}$: body c.m. position in ARF

$\bar{A}$: acceleration of ARF origin in IRF

$\bar{g}$: local gravity acceleration

$\bar{T}$: force(s) coming from the tether

$\bar{F}$: other external forces (thrusters firing, imposed perturbations).

No Coriolis force is present because the ARF does not rotate. The rotational differential equations for the Orbiter or the Satellite are represented by the Euler equations. The rotational motion is described by means of 3 Euler angles, deriving from the integration of the Euler equations (motion about the centre of mass).

2.5 Other Features

No environmental model has been implemented: aerodynamic drag and electromagnetic forces on the tether were considered negligible, even if the possibility to input forces on the mass points is foreseen.

In general arbitrary forces can be introduced to analyse the system behaviour under specified perturbations.

All the Satellite thrusters are modelled and their misalignements, as source of attitude perturbations, considered.

The control laws of the tether length and in-plane & out-of-plane libration developed for the TSS program have been implemented.

The Orbiter attitude may have an indirect but important impact on the Satellite behaviour during some mission phases, so it has been included in the model together with a very simplified model of the digital autopilot and reaction control system.

Due to lack of data on tether characteristics, no damping has been considered for the system oscillation, this resulting in a conservative hypothesis. The tether torsional stiffness is negligible and so it is not taken into account in this program.

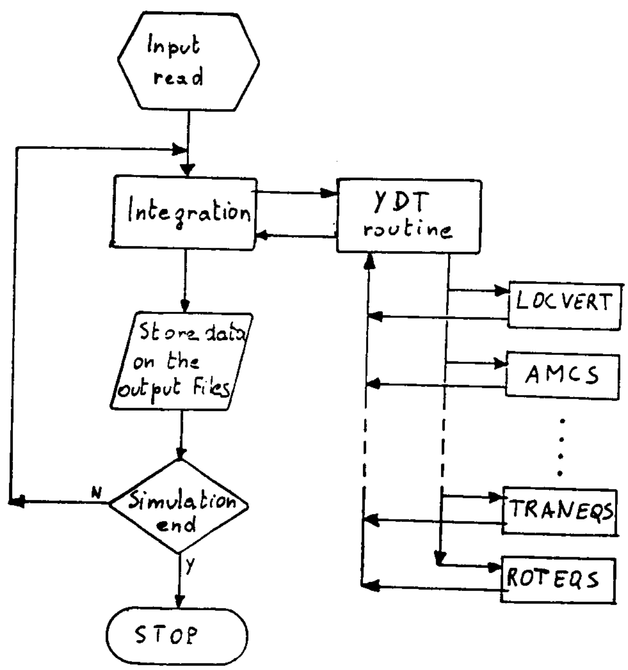
A new feature which will be introduced in the program is represented by the addition of flexible modes on the Satellite , simulating two deployable booms.

The need to model in an easy way the flexibilities of the deployer boom on the Orbiter, expecially at very short tether length, is being investigated.

3 - SOFTWARE DESCRIPTION

The general architecture of the program is presented in figure 4. The simulation program is coded in FORTRAN 77 and runs on a VAX 785 machine.

Fig. 4



The YDT routine computes, time by time, the state vector derivative to be integrated. It determines all the force and torque vectors acting on each part of the system, via the management of the call of several subroutines, each describing a particular item (see table 1),allowing to build the differential equations.

Subroutine	Function
LOCVERT	Sat. attitude wrt local vertical computation
AMCS	AMCS model
ACS	Simplified AMCS model
INLINE	In-line thrusters command logic
PTCHCMD	Commanded libration pitch angle
LIBRCTL	Libration control logic
ORBATT	Orbiter attitude control system model
TENSCMD	Commanded tether tension
REELEQ	Tether reeling equation
VARMAS	Tether variable characteristics computation
THRUST	Thrusters forces and torques computation
ORBEQS	Orbital equations
TENSION	Tether tension force acting on each body
GRAVITY	Gravity forces computation
TRANEQS	Translational equations for each body
ROTEQS	Rotational equations (Satellite,Orbiter)

TABLE 1

The program has been conceived in a modular way so that the change of the generic module can be friendly performed, as well as new routines introduced and other bypassed.

The integrator is a 4th order Runge-Kutta algorithm.

The output of the program are:

- diagrams of selected variables;

- print-outs;

- restart file, which allows for the restart of the simulation from the end of a previous one;

- output file , stored on tape, containing the time history of all the variables needed as input for the verification and testing programs.

The dynamic part of the program is being checked via comparison runs to be performed with a qualified simulation program.

4 - REFERENCES

1 - C.S. Bodley, A.C. Park - TSS Orbital Dynamics Model 1B, Martin Marietta Corporation, June 1984, Contract no. NAS8-36000

2 - C.S. Bodley, A.C. Park, P.J. Grosserode - TSS Orbital Dynamics Model 1B (Revision A), Martin Marietta Corp.,

February 1985, Contract no. NAS8-36000

3 - DCAP User Manual - Vol 1 Theory, Aeritalia

ESA Contract no. 4045/79/NL/AK (SC)

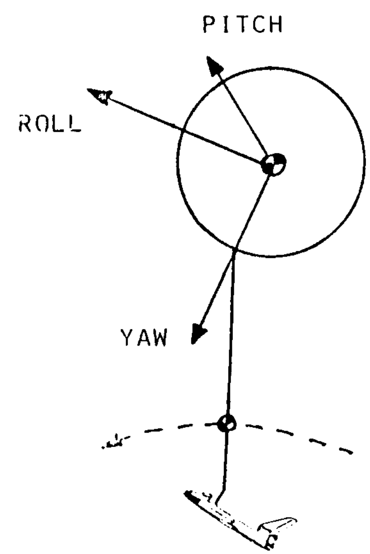
VIEWGRAPHS

TSS SUBSATELLITE ATTITUDE DYNAMICS AND CONTROL LAWS VERIFICATION PROGRAMS

TDS WORKSHOP '86

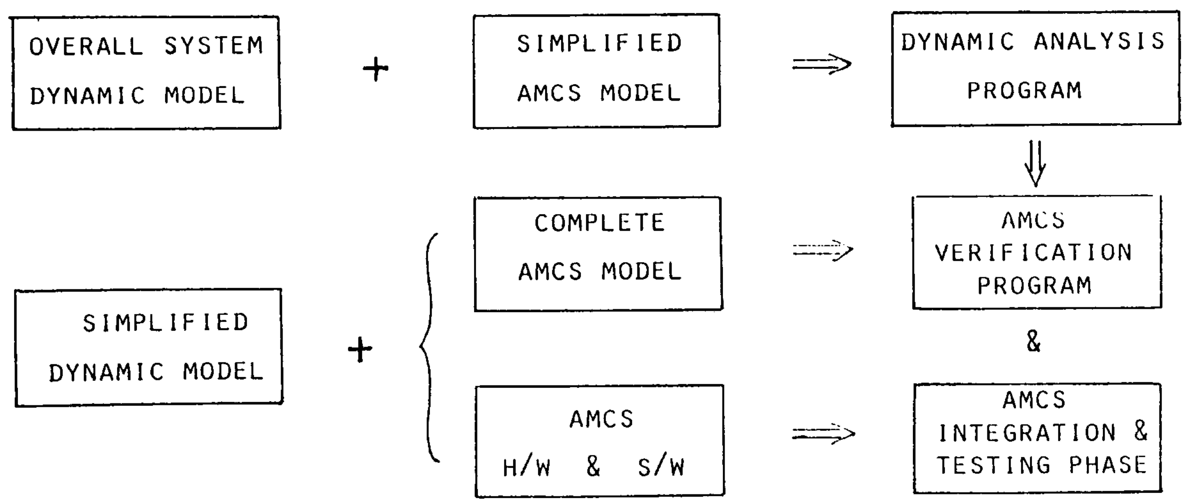
FRAMEWORK : VERIFICATION AND TESTING OF THE TSS SUBSATELLITE ATTITUDE MEASUREMENT AND CONTROL SUBSYSTEM (AMCS) DESIGN TO BE PERFORMED BY AERITALIA

SELECTED MISSION: 1^{ST} ELECTRODYNAMIC MISSION



TDS WORKSHOP '86

* A DYNAMIC ANALYSIS OF THE TSS SYSTEM IS REQUIRED TO SUPPORT:
  - THE VERIFICATION BY ANALYSIS OF THE AMCS DESIGN;
  - THE AMCS INTEGRATION/TESTING PHASE.

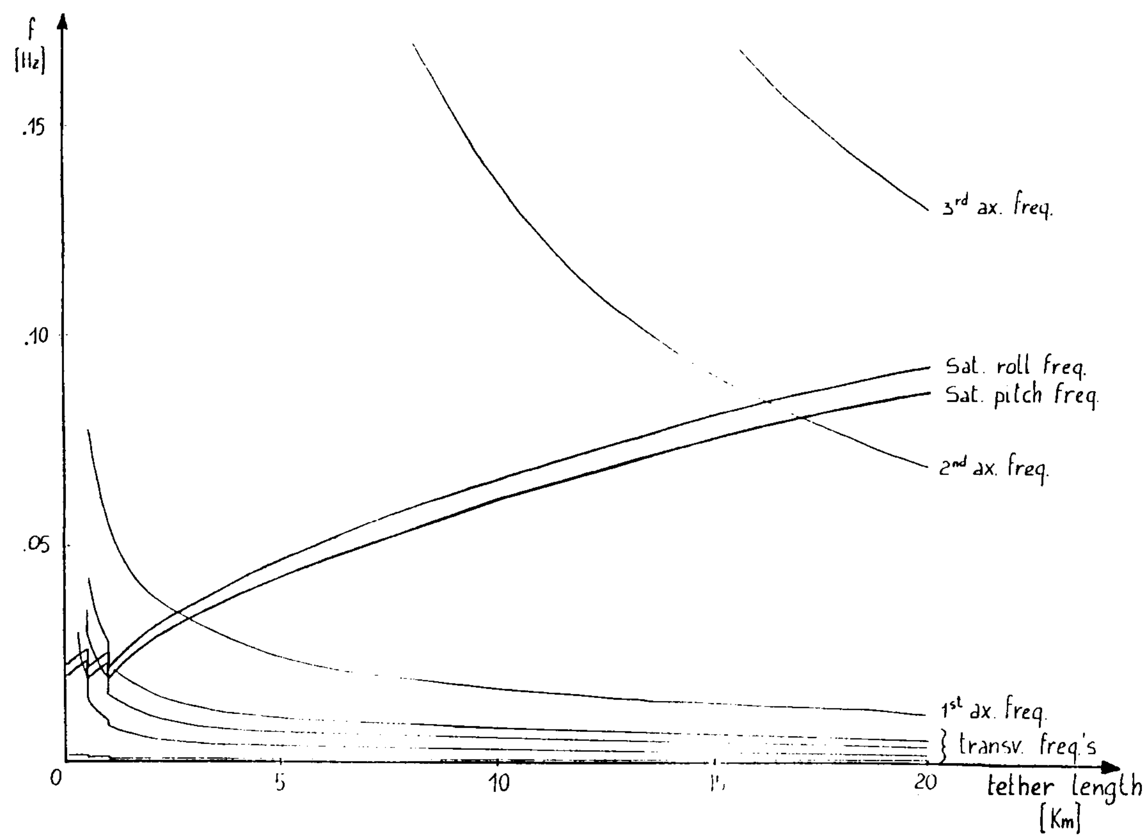


DYNAMIC ANALYSIS PROGRAM

* IT HAS BEEN DEVELOPED IN ORDER TO:

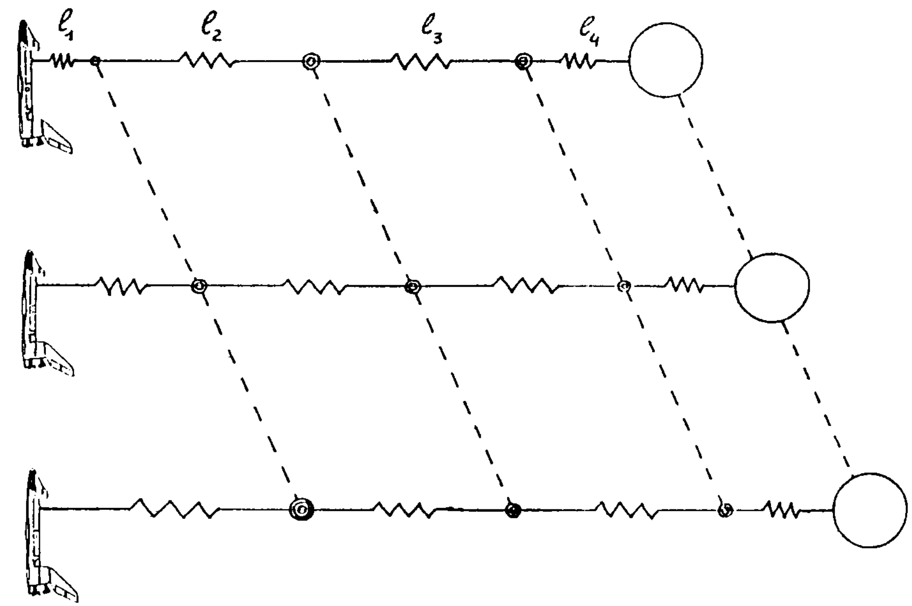
  - INVESTIGATE THE SYSTEM DYNAMICS (WITH A PARTICULAR CARE FOR THE SATELLITE ATTITUDE), AND IDENTIFY POTENTIALLY CRITICAL AREAS FOR AMCS PERFORMANCE VERIFICATION;

  - PROVIDE REALISTIC INPUT DATA FOR VERIFICATION AND TESTING PHASES.



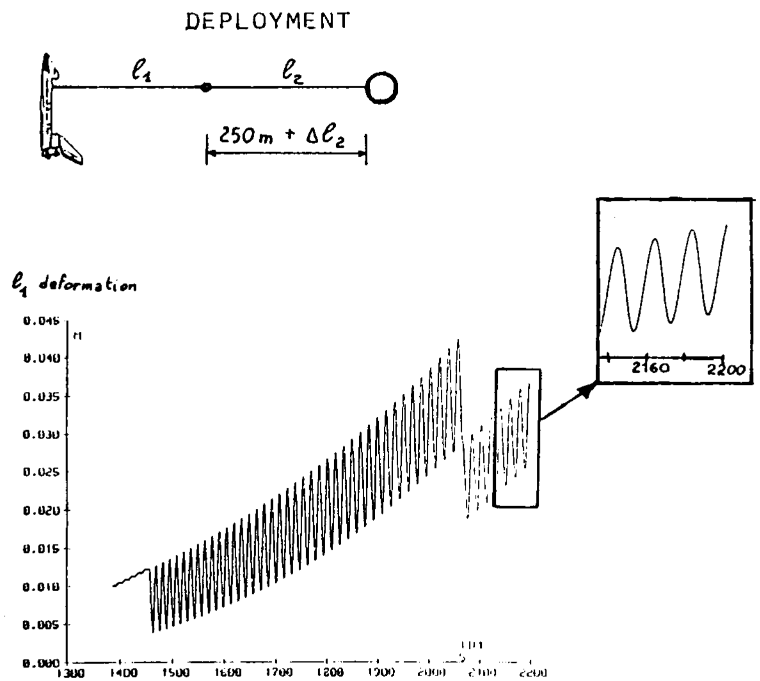
SYSTEM FREQUENCIES

TDS WORKSHOP '86

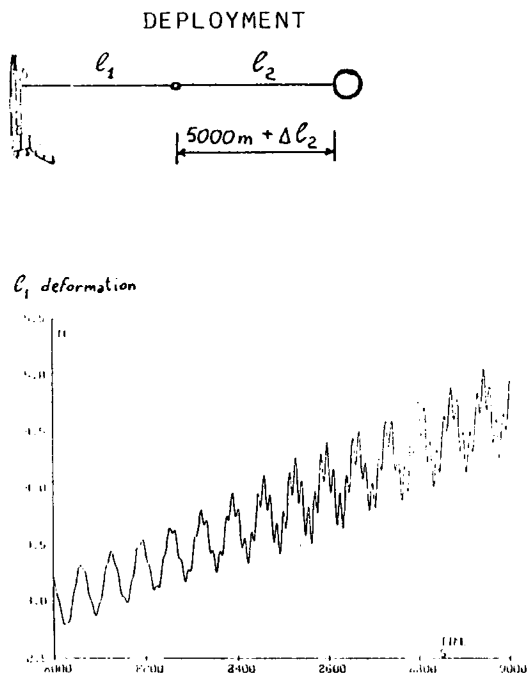


TETHER MODEL

TDS WORKSHOP '86

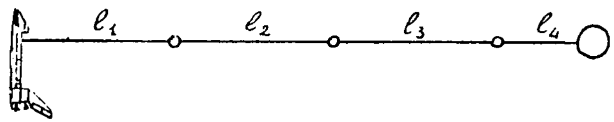


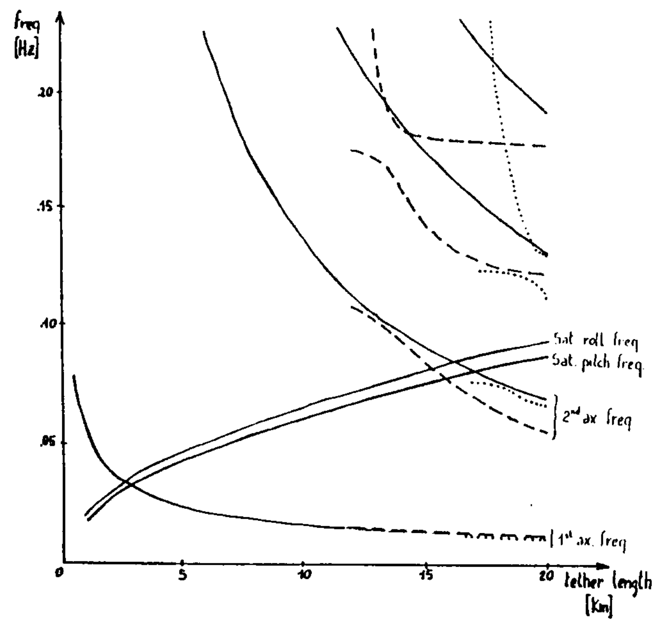
SYSTEM RESPONSE TO IN-LINE THRUSTERS FIRING



SYSTEM RESPONSE TO AN EXCITATION OF THE SAME FREQUENCY OF SUBSATELLITE OSCILLATIONS

TDS WORKSHOP '86





– – – – – – over 13000 m :

ℓ_2 = 4500 m

ℓ_3 = 4500 m

ℓ_4 = 2500 m

.... over 17000 m :

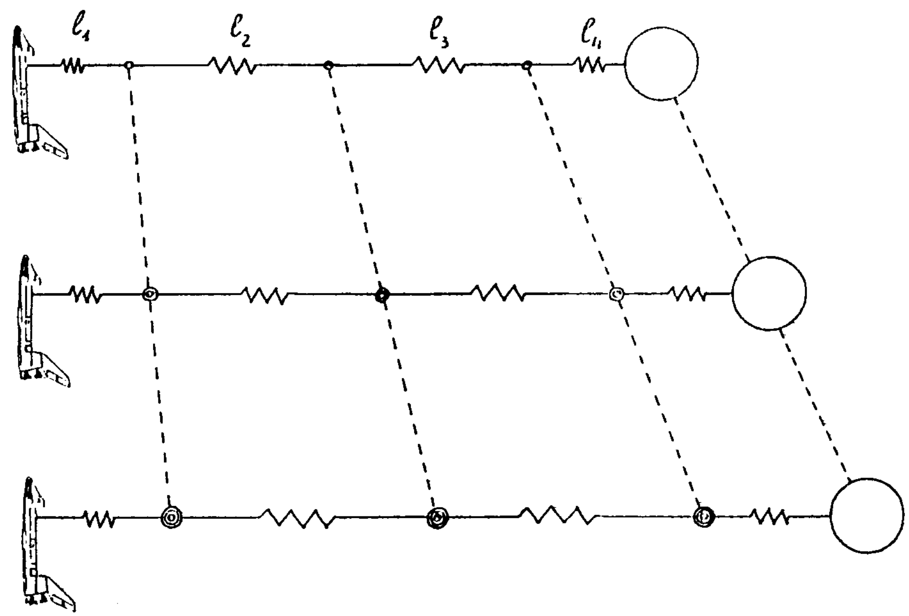
ℓ_2 = 6600 m

ℓ_3 = 6600 m

ℓ_4 = 3300 m

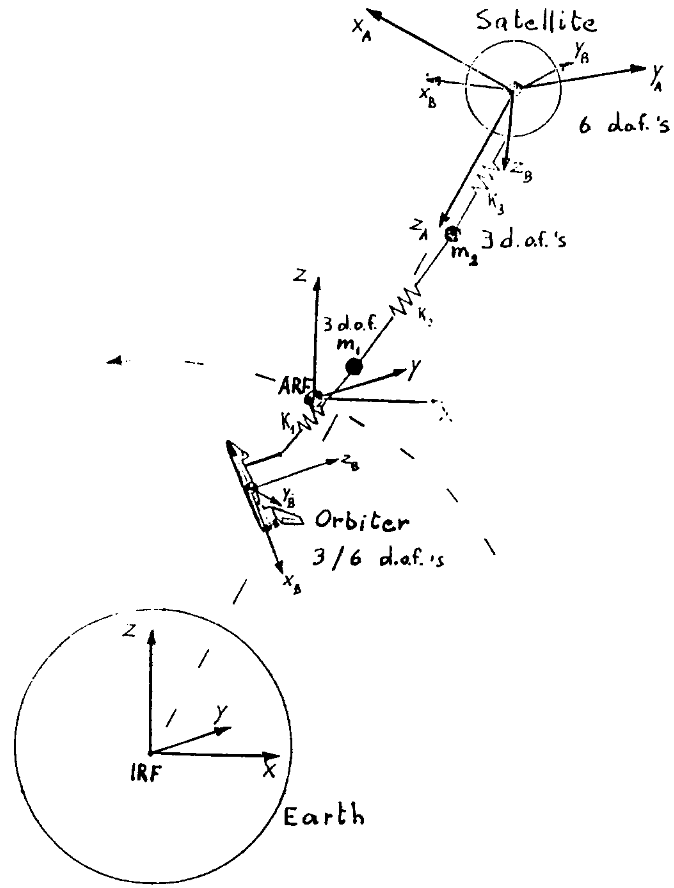
ACTUAL SYSTEM AND
MODEL FREQUENCIES

TDS WORKSHOP '86



TETHER ALTERNATIVE MODEL

TDS WORKSHOP '86



SYSTEM MODEL

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* THE MOTION OF THE SYSTEM IS DESCRIBED WRT THE ACCELERATING REFERENCE FRAME (ARF).
* THE DIFFERENTIAL EQUATIONS ARE DERIVED IMPOSING FOR EACH BODY THE CONDITION OF DYNAMIC EQUILIBRIUM.
* THE TRANSLATION EQUATION FOR THE GENERIC BODY IS :

$$M \ddot{\bar{x}} = - M \bar{A} + M \bar{G} + \bar{T} + \bar{F}$$

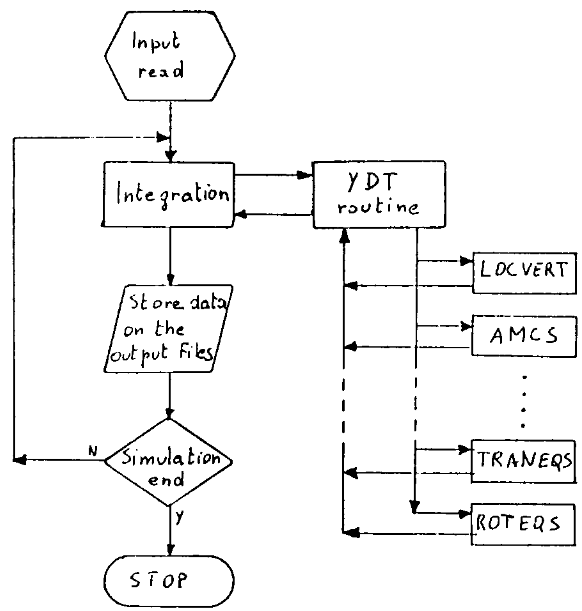
$\bar{x}$ = BODY'S C.M. POSITION IN ARF
$\bar{A}$ = ACCELERATION OF ARF ORIGIN IN THE INERTIAL FRAME
$\bar{G}$ = LOCAL GRAVITY ACCELERATION
$\bar{T}$ = FORCE(S) COMING FROM THE TETHER
$\bar{F}$ = OTHER EXTERNAL FORCES (THRUSTER FIRING, IMPOSED PERTURBATIONS)

* THE ROTATIONAL MOTION IS DESCRIBED ABOUT THE CENTER OF MASS OF EACH BODY BY MEANS OF THE EULER EQUATIONS.

* OTHER FEATURES

- NO ENVIROMENTAL MODEL
- ARBITRARY FORCES CAN BE IMPOSED ON EACH BODY
- SATELLITE THRUSTERS MISALIGNEMENTS CONSIDERED
- ORBITER ATTITUDE AND SIMPLIFIED MODEL OF DAP/RCS
- NO DAMPING (CONSERVATIVE HYPOTHESIS)
- TETHER CONTROL LAW AND LIBRATION CONTROL LAW IMPLEMENTED
- IN PROGRESS :
  . DEPLOYABLE BOOMS ON THE SATELLITE
  . FLEXIBILITY OF THE DEPLOYER BOOM ON THE ORBITER

TDS WORKSHOP '86



PROGRAM GENERAL FLOW CHART